BRL

MEMORANDUM REPORT NO. 1280
JUNE 1960

SHOCK PRESSURES IN TUNNELS ORIENTED FACE-ON AND SIDE-ON TO A LONG DURATION BLAST WAVE

Robert O. Clark
William J. Taylor

Department of the Army Project No. 5B03-04-002
Ordnance Management Structure Code No. 5010.21.815

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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ABERDEEN PROVING GROUND, MARYLAND

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RDClark/WJTaylor/sec
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ABSTRACT

The orientation of a tunnel entrance with respect to the burst point of a bomb plays a major part in determining the strength of shock propagated through the tunnel. Data from tunnels oriented face-on and side-on to a blast wave are compared to a shock tube with an area change at the diaphragm. The analogy permits data to be extrapolated to high shock strengths.

LIST OF FIGURES

LIST OF SYMBOLS

P_1 Ambient Pressure

P_2 Absolute Pressure

P_4 Absolute Compression Chamber Pressure

P_5 Absolute Reflected Shock Pressure

P_c Compression Chamber Overpressure

P_s Shock Overpressure

P' Transmitted Pressure

NOTATIONS

$$P_{21} = \frac{P_2}{P_1}$$

$$P_{41} = \frac{P_4}{P_1}$$

$$P_{51} = \frac{P_5}{P_1}$$

INTRODUCTION

This report is intended to aid the designers of protective construction in their pursuit of information dealing with the behavior of blast waves in tunnels. The paper puts forth an analogy which will permit one to predict reasonably well, the pressure which may be expected at certain points in a tunnel system. Specifically, it deals with the maximum pressures that are developed in tunnels, for two orientations - the face-on tunnel and the tunnel orientated side-on to the blast wave. The analogy compares the conditions at the tunnel entrance with the conditions across a pressure-laden diaphragm in a shock tube. Curves which relate the shock pressures to the chamber pressures are presented along with some data from tunnel experiments conducted at BRL. BRL data were obtained up to a shock strength of 8, approximately 100 psi overpressure when the atmospheric pressure is 14.7 psi, but the theoretical curves are plotted to a shock strength of 30. It is felt that the manner in which the data support the analogy at the lower end of the curve permit reasonable prediction of pressure beyond the shock strength tested.

This report deals with simulated large explosions where there is virtually no decay during the shock formation time in the tunnel. The shock tube data presented were obtained with a step shock wave which simulated this case. Peaked shock waves would yield data with pressure values less than those which are presented in this report.

ORIENTATION AND ENTRANCE GEOMETRY

The orientation of a tunnel entrance with respect to the burst point of a bomb, plays a major part in the determination of the strength of the shock wave that is propagated through the tunnel. Further, the geometry of the area in the vicinity of the entrance influences the shock in the tunnel. For instance, for the face-on case, if the tunnel entrance has a large reflecting area surrounding it, like a tunnel entrance in the face of a large sheer cliff, a sizeable reflected pressure region would exist when a shock wave was directed at the cliff. This reflected pressure region

enhances the shock wave that is propagated in the tunnel. On the other hand, the entrance of a thin wall pipe would present no reflecting area and would merely confine the shock wave to a one dimensional expansion. In configuration (a) of Figure 1 there is no reflecting area so when the shock wave is directed at the configuration there is just a one dimensional expansion of the wave after it enters the pipe. In (b) there is some reflecting area and hence a partial enhancement of the wave. Case (c) is the most severe condition because it permits the most sustaining reflected pressure region.

With a side-on tunnel orientation, i.e., the tunnel positioned with its axis perpendicular to the direction of blast propagation, the absence of a reflecting zone will limit the pressure at the entrance to the side-on or incident shock pressure. The shock pressure in the tunnel will be less than the incident applied shock.

One can see now that the pressure phenomena at the entrance of a tunnel will vary with the orientation of the tunnel and surrounding area.

THE COMPRESSED GAS SHOCK TUBE

A compressed gas shock tube has a compression chamber and an expansion chamber which are separated by a breakable diaphragm. A pressure differential is created across the diaphragm by putting an overpressure of gas in the compression chamber, by evacuating the expansion chamber, or a combination of both. A shock wave is formed when the diaphragm is ruptured and the released gas exits into the expansion chamber. The duration of the shock wave that is generated is a function of the compression chamber length,the compression chamber pressure, and the distance from the diaphragm to the measuring point (Reference 1). When the compression chamber area is much larger than the expansion chamber area, greater shock pressures are developed

in the expansion chamber for a given chamber pressure. In Figure 2, the pressure relationships are plotted for both the simple shock tube and the tube with an area change at the diaphragm (References 2, 3, & 4).

SHOCK TUBE ANALOGY

Consider now the face-on tunnel with a large reflection region surrounding the tunnel entrance: the situation at shock impingement time is analogous to the shock tube with an area discontinuity at the diaphragm.

The analogy is shown in Figure 3 where the stagnated reflected pressure region P_5 is equated to the compression chamber pressure P_c and the diaphragm has a zero breaking time. For case (a) the driver, or reflected pressure, P_5 is a result of the reflection of P_2 and hence the new shock P_2' can be related to P_2. This theoretical relationship, expressed in terms of pressure ratios is shown in Figure 4 along with some data points from BRL experiments. The relationship plotted considers the temperature of the gas in the compression chamber to be the same temperature as that in the reflected shock P_5.

The data points were obtained by attaching blind flanges to the BRL shock tube and producing shots against the flanges. The tunnels with piezo gages attached to the walls were attached to the flanges. One set of data was obtained on the 24" diameter tube with a 1" pipe in the flange serving as the tunnel. The ratio of areas is quite large for this case. Other sets of data were obtained on the 4 x 15" tube with 1" and 2" diameter pipes. Note that two data points are noticeable below the curve. These points were obtained near the entrance, in a region where the transmitted shock was not fully developed. In general the data fit the curve and substantiate the analogy.

From this plot one can see that the shock wave that is transmitted down the tunnel is stronger than the incident wave. For instance, an incident shock strength of 7 produces a new shock strength of 10.2. At an atmospheric pressure of 14.7 psi this is an overpressure increase from 88 to 135. A

reflecting wall or door in the tunnel will receive 735 psi as opposed to 425 psi. An extrapolation of these data to a P_{21} of 15 incident at the tunnel yields a P_{21}' of 22.2. At an atmospheric pressure of 14.7 this is a pressure increase from 206 to 312 psi.

SHOCK FORMATION

It is obvious that some formation time is required to build the shock wave from the P_2 value to P_2'. This time is a function of the tunnel diameter, the shock pressure, and the area of the reflecting surface. In the preceding discussion the area was considered to be very large, an "infinite" baffle, hence the new shock wave generated was the maximum possible for the given value of incident pressure. Baffles that are less than "effectively infinite" will produce P_2' values less than the maximum shown in the Figure 4.

With very large baffles, the thickness of the reflected pressure region is sufficient to establish steady flow in the orifice. One can see then that the time required for a layer of reflected pressure sufficiently thick to provide steady flow, must be inherently related to the orifice diameter.

From Figure 5 we can see that initially the pressure in the tunnel is that of the applied pressure, hence gages positioned close to the orifice will not measure the fully developed shock pressure. Those close to the orifice positions also show a complex wave form that comprises both the incident wave and some part of the higher pressures from the reflection zone. The distance required for these two pressures to coalesce and form the maximum shock is considered the formation distance. This distance is generally expressed in tunnel diameters and based on the BRL data to date, it will be between 5 and 20 tunnel diameters.

One can see now that if the baffle diameter is not large enough to sustain the reflected pressure until the new shock wave is fully developed, the formation distance will be shorter and the maximum possible shock as predicted from Figure 4 will not be obtained.

Figure 6 is a plot of maximum pressure as a function of pipe diameter for two shock strengths. The sketch on the figure shows the physical arrangement of the experiment. The pressure ratios at 0 diameters are that of the incident applied pressures and not the reflected pressures on the baffle, and the maximum pressures as predicted from Figure 4 are shown by the dashed lines. The discrete location of the gages present the possibility of missing the precise pressure maximum.

THE SIDE-ON TUNNEL

When a shock wave approaches a tunnel so that the tunnel axis is 90 degrees to the direction of propagation of the applied shock, the shock in the tunnel (transmitted shock) is less than the incident applied shock. The driving pressure here for the new shock wave is approximately the incident pressure of the applied wave, but the gas is not stationary; it is moving across the ground with a velocity equal to the particle velocity of the applied shock. It is also a hot gas. If we consider this gas velocity to be zero, one can again revert to the shock tube analogy. The validity of mathematically bringing the gas velocity to zero without applying a correction factor is open to question. Intuitively one feels that because of the gas velocity, the transmitted pressure will be less, and that a correction factor would adjust the result in that direction.

Figure 7 shows data obtained from tunnels mounted side-on to the shock tube and the theoretical relationship for a large area compression chamber. Again the gas in the would-be compression chamber has been corrected to the temperature of the shock wave P_{21}.

In Figure 8 the face-on and side-on orientations are compared so that one may observe the difference in maximum pressure as a result of the orientation. The advantage gained by the side-on orientation is obvious.

TUNNEL SIDE-ON TO A TUNNEL

Another consideration with the side-on tunnel is the tunnel that is side-on to another tunnel. Here the initial shock wave is confined to a tunnel which has the same area as the joining tunnel. It is felt that because

of the restricted air supply the conditions more nearly resembles the simple shock tube configuration. Data from experiments conducted with this configuration are plotted in Figure 9 with the relationship for a simple shock tube.

CONFIGURATION ANALYSIS

The three theoretical curves which have been presented can be applied to three types of entrance conditions. Figure 10 shows a tunnel system and the three curves plotted in terms of pressure rather than pressure ratio. The lengths of the tunnels will be sufficient to permit the maximum shock to develop and we will assume no attenuation due to tunnel wall roughness or the one dimensional expansion.

For a very large bomb burst directly over Tunnel A, where the pressure at the entrance before reflection from the ground is 100 psi, the pressure developed in Tunnel A will be 160 psi. This shock moving across the entrance to B tunnel propagates a new shock of 75 psi into the tunnel. Curve B is used here because Tunnel A is much larger than Tunnel B. In Tunnel C the pressure as read from Curve C, the relationship for a 1 to 1 shock tube, is 25 psi.

In an analysis such as this, one must bear in mind that tunnels are not infinitely long and that there will be reflections and rarefactions in the system. For short tunnels, reflection from blind ends will be greater than the pressure shown here as maximum pressures. In very long tunnels the shock wave attenuation may be significant, so that the starting pressure in secondary tunnels will not be those described in Figure 10. Experiments presently in process at BRL are designed to yield information on this attenuation history of the blast waves.

It is believed that information, presented will be of value to persons concerned with the protective construction problem.

Robert O. Clark
ROBERT O. CLARK

William J. Taylor
WILLIAM J. TAYLOR

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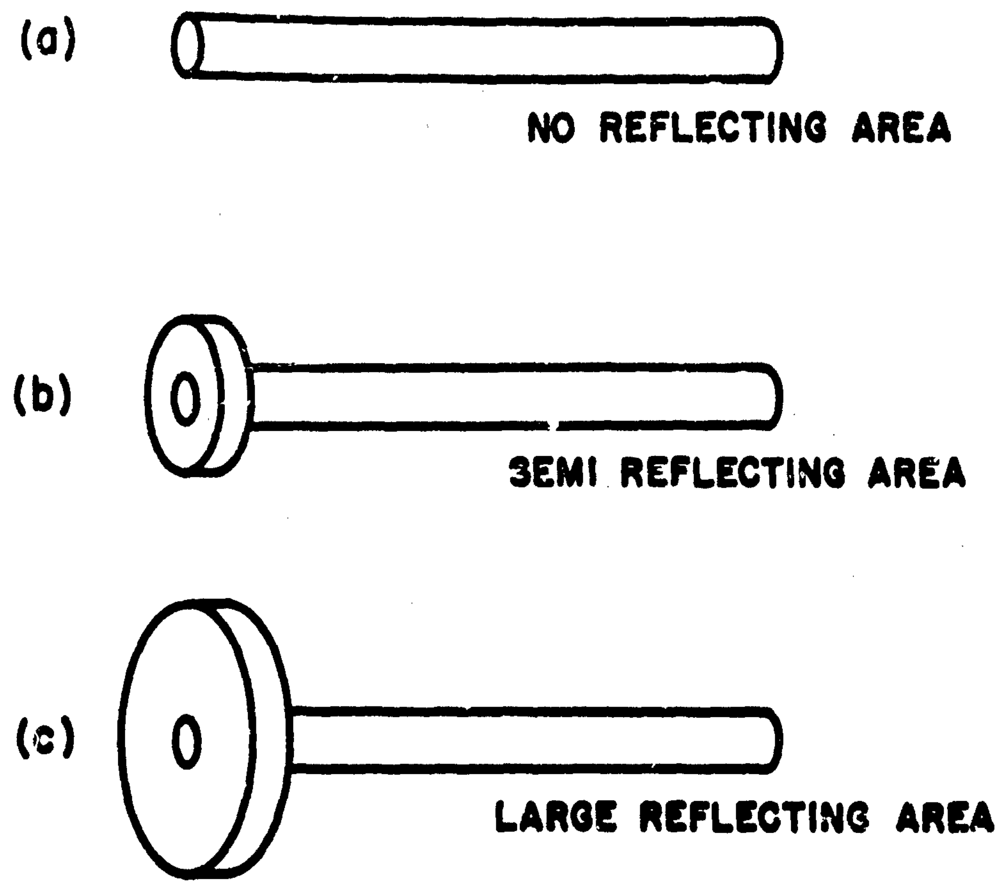

FIG. 1 – EXAMPLES OF REFLECTING AREAS

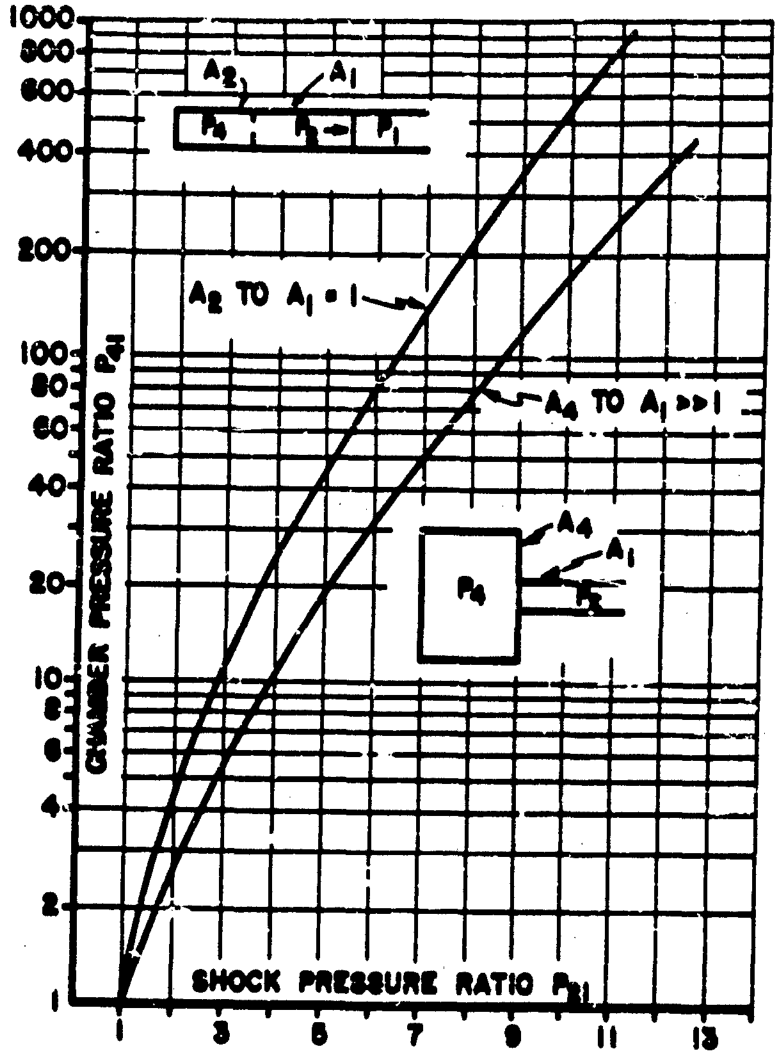

FIG. 2 – PERFORMANCE COMPARISON–SIMPLE AND VARIABLE GEOMETRY SHOCK TUBES

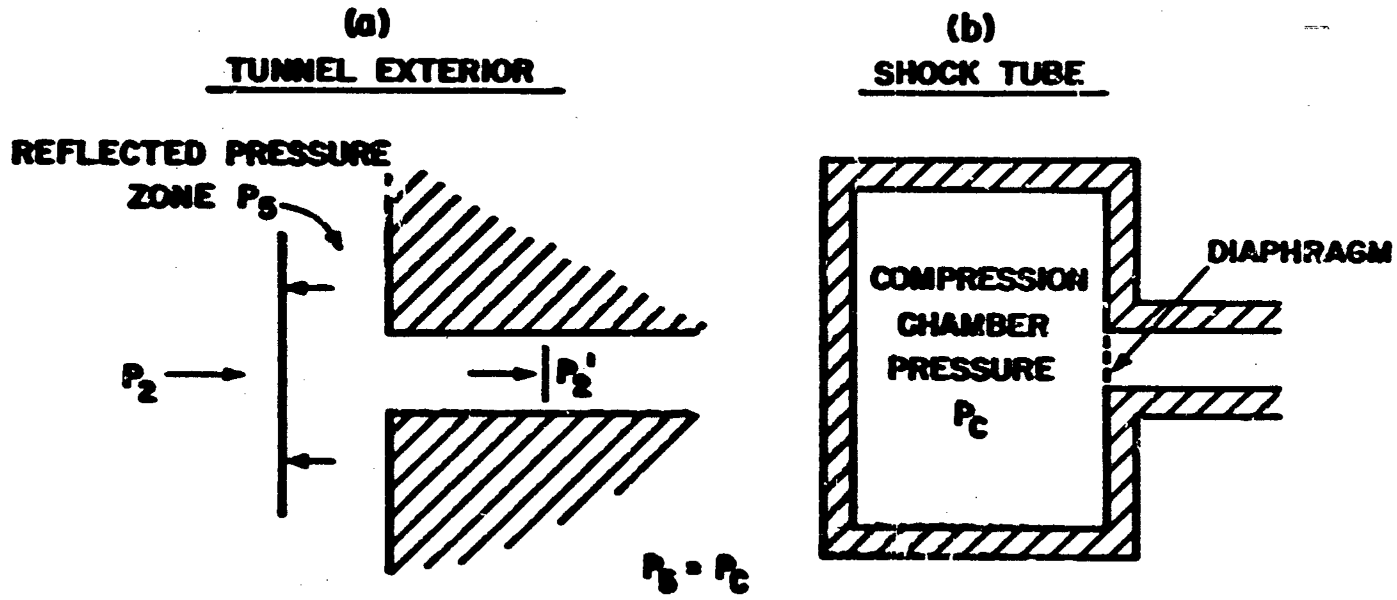

FIG. 3 – COMPARISON OF TUNNEL ENTRANCE WITH SHOCK TUBE

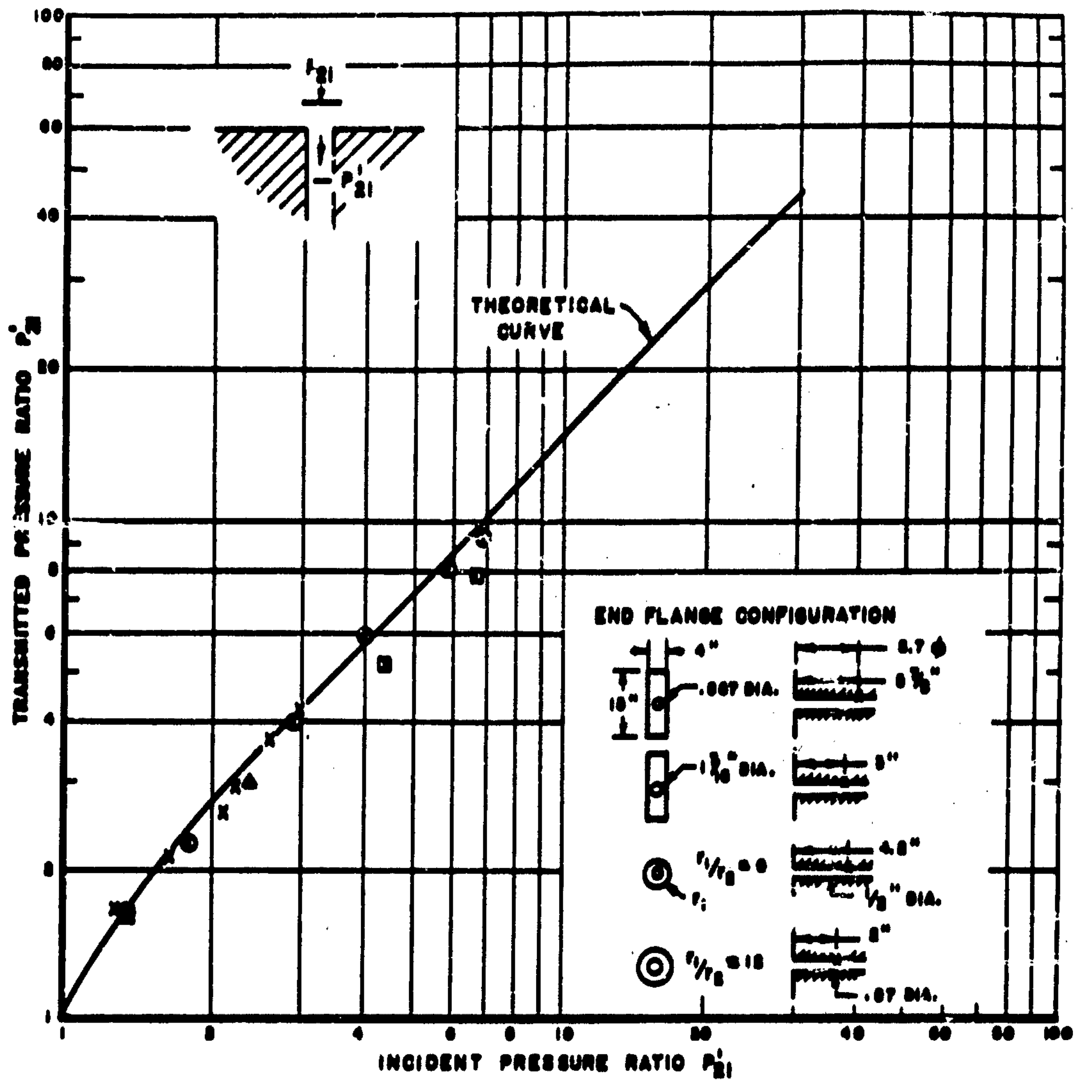

FIG. 4 – INCIDENT vs. TRANSMITTED PRESSURE RATIO'S FOR 0° TUNNEL

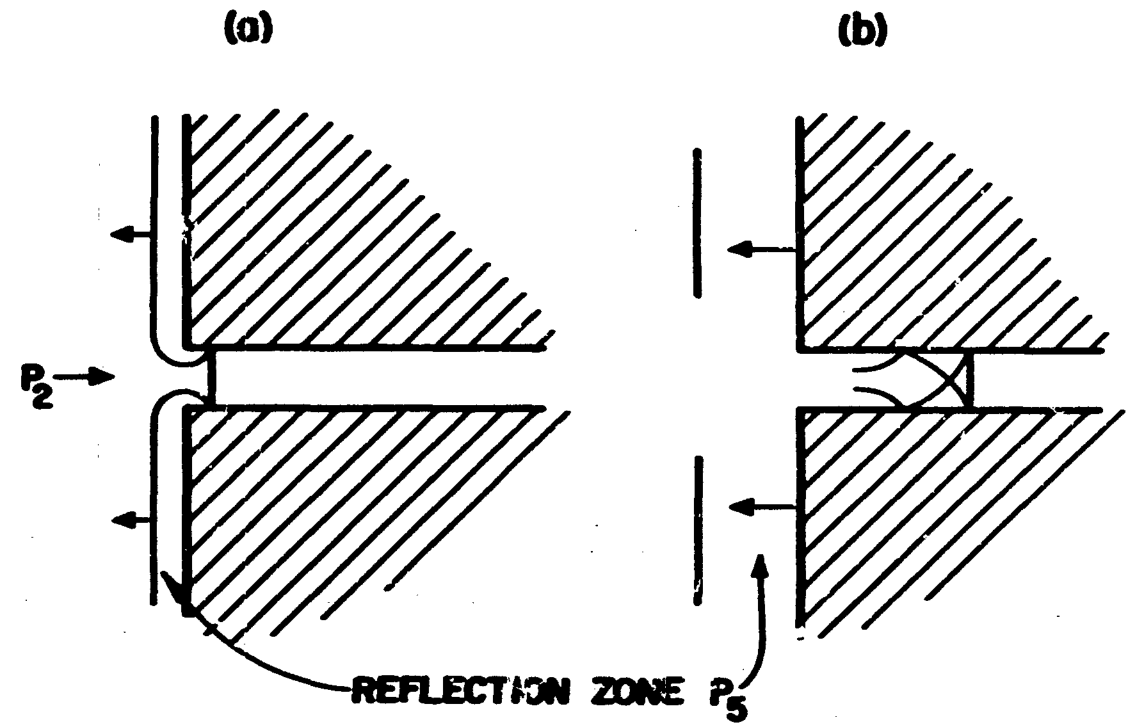

FIG. 5 – SHOCK FORMATION IN FACE ON TUNNEL

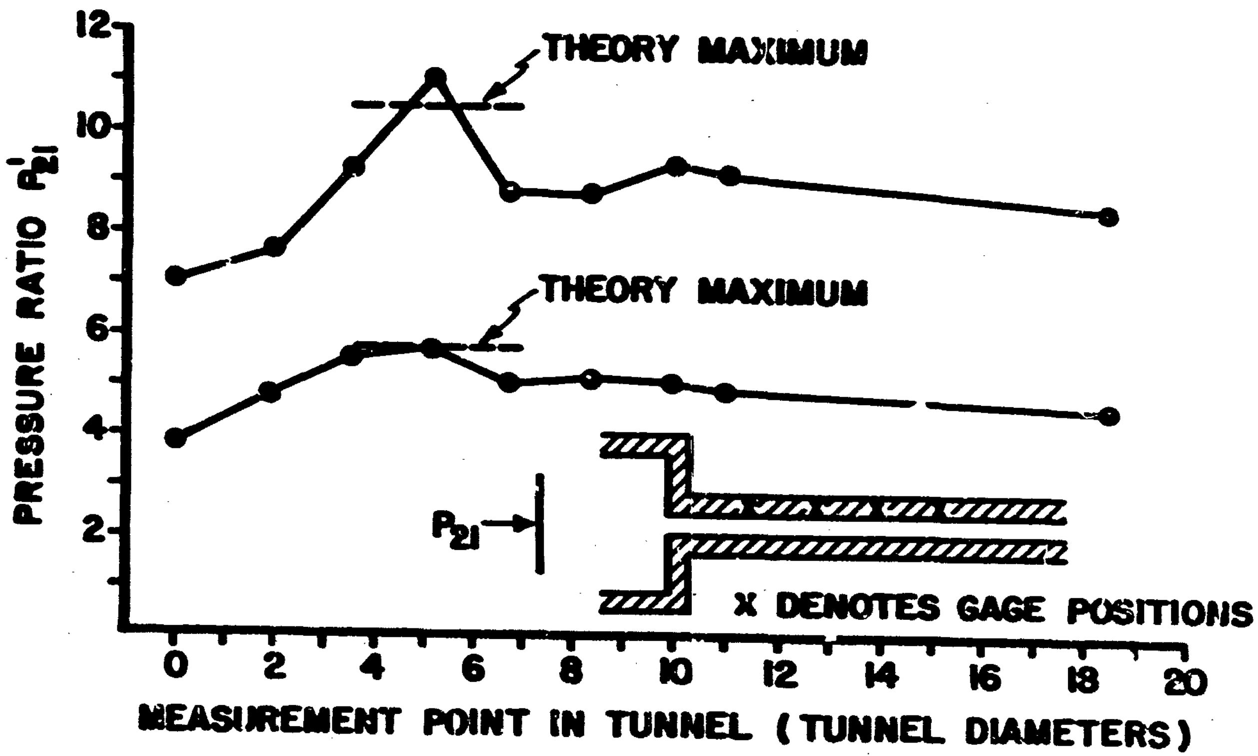

FIG. 6 – SHOCK FORMATION DISTANCE AS A FUNCTION OF PRESSURE RATIO

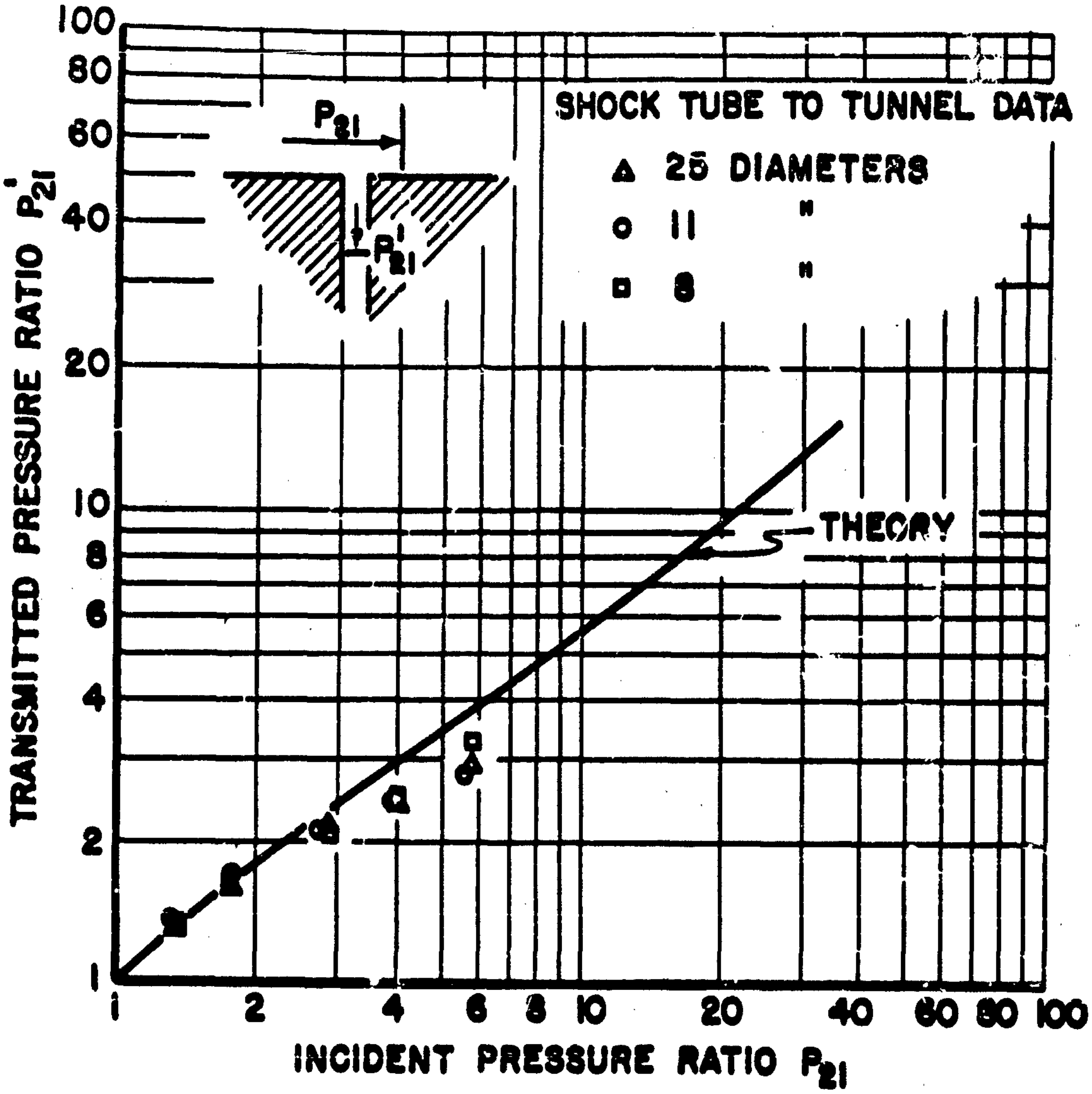

FIG. 7 – INCIDENT VS TRANSMITTED PRESSURE RATIO FOR 90° TUNNEL

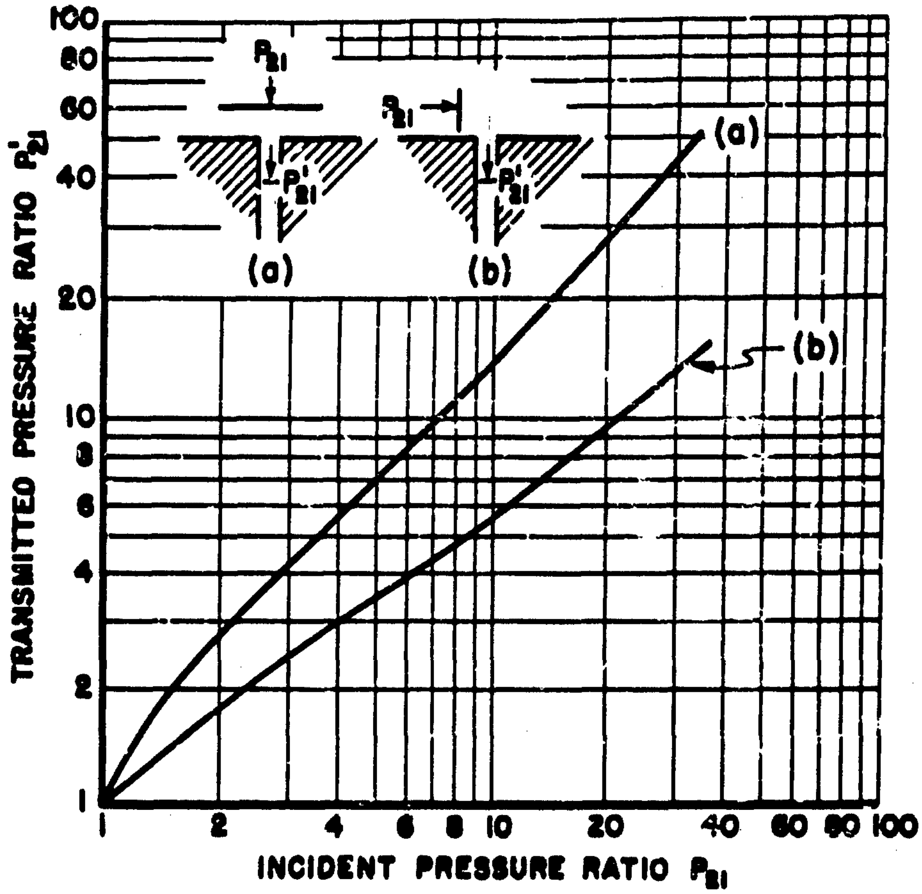

FIG. 8 - TRANSMITTED SHOCK PRESSURE RATIO AS A FUNCTION OF ORIENTATION AND PRESSURE

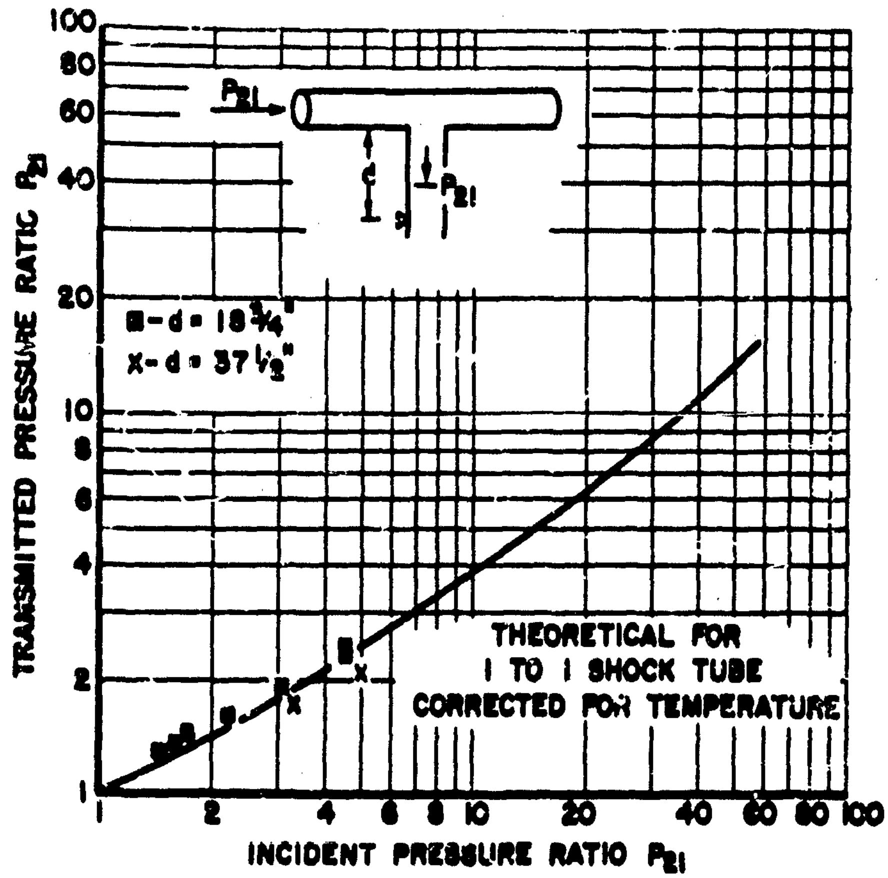

FIG. 9 – INCIDENT VS. TRANSMITTED SHOCK PRESSURE RATIO, TUNNEL JOINED TO AN EQUAL AREA TUNNEL

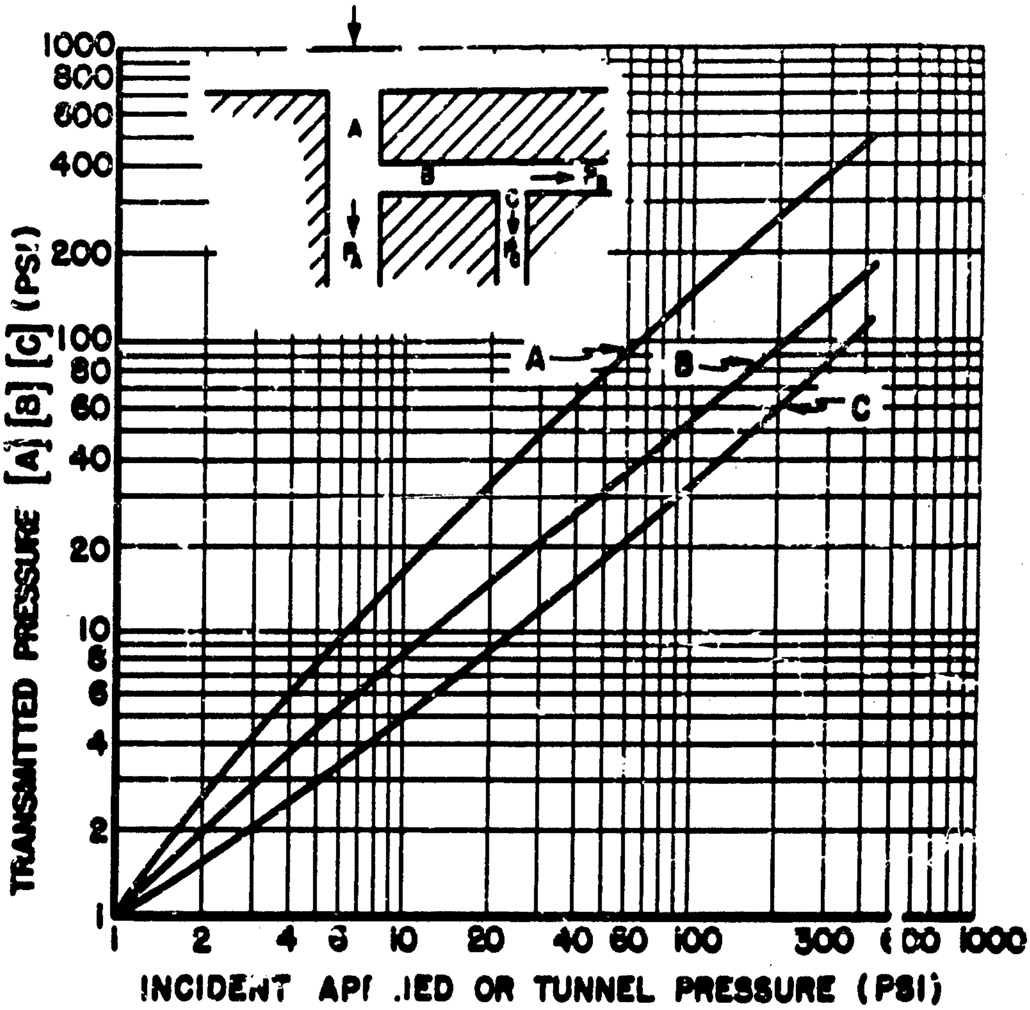

FIG. 10 – OVERPRESSURES DEVELOPED IN A TUNNEL CONFIGURATION